Extrusion of Al-Si alloy compacts under conventional conditions and in the semi-solid state

K Zyguła[1], O Lypchanskyi[1], M Wojtaszek[1], T Śleboda[1],

[1]AGH University of Science and Technology, Faculty of Metals Engineering and Industrial Computer Science, Av. Mickiewicza 30, 30-059 Cracow, PL

kzygula@agh.edu.pl

Abstract. In this research work the results of hot extrusion process of aluminium alloy compacts conducted at the temperature of conventional hot extrusion as well as at the temperature range corresponding to the semi-solid state were presented. Initial material was prepared by uniaxial pressing of Al17Si5Fe3Cu1.1Mg0.6Zr alloy powder. The extrusion process was carried out under isothermal conditions, and the temperature stability was strictly controlled. The changes of extrusion force in relation to punch displacement were recorded during hot deformation to demonstrate the effects associated with the appearance of the liquid phase in the volume of the processed material. After extrusion the samples were cooled in water as well as at room temperature. The influence of temperature of extrusion and the resulting fraction of the liquid phase in the processed material on its microstructure and chosen mechanical properties were determined. Mechanical properties of the examined alloy after deformation were carried out by measuring the hardness and in uniaxial compression tests. Additionally, one of the compacts was remelted and cast, what made possible comparison of the microstructure and chosen properties of the obtained products. In the result of the investigations it has been proved, that extrusion in semi-sold state results in reduction of forces necessary to complete deformation process and leads to obtaining the material with good mechanical properties and fine-grained, favourable microstructure.

1. Introduction

Aluminium alloys with addition of silicon known as 3xxx or 4xxx series alloys are commonly used in casting of car engine cylinder head [1]. Moreover, extruded aluminium alloys found its application in automotive industry as car frame, resulting in its weight reduction. Due to the combination of low density and excellent corrosion resistance such alloys are widely used in aerospace industry [2,3].
Semi-solid processing, also know as thixoforming, is a technology which combines traditional hot forming with casting process. Most important assumption of semi-solid method is deformation between solidus and liquidus temperature of the processed material. Aluminium alloys are widely used in semi-solid processing. Components obtained by such method have good mechanical properties and advantageous microstructure. Moreover, thixoformed products can be successfully T6 heat treated to improve their properties [4,5,6]. Hot forming of metals above the solidus line leads to change in the deformation mechanism. Deformation occurs along the grain boundaries, where the liquid phase is located. Because of decrease of loads during deformation in the semi-solid range, the process is economically attractive, and gives possibilities to obtain near-net shape products [7,8].

2. Experimental research

2.1. Aim and scope of study

The aim of the research was to evaluate the microstructure and chosen mechanical properties of compacts made of Al17Si5Fe3Cu1.1Mg0.6Zr (Al17Si) alloy powder, extruded in isothermal conditions in both the temperature of conventional hot forming processes and in the semi-solid state. The investigations involved production of compacts by hot pressing process and then extrusion in various temperatures. To determine the temperature of transition into semi-solid state, differential scanning calorimetry and thermographic tests were carried out. The microstructure of the investigated materials after deformation was analysed by light microscopy. To study the influence of the temperature of extrusion on the mechanical properties of the examined material, hardness measurements and uniaxial compression tests were conducted.

2.2. Material for the investigations

The initial material used in hot pressing process was Al17Si alloy powder with chemical composition given in table 1. A size of powder particles did not exceed 60 µm. Compaction process was carried out on hydraulic press. The temperature of hot pressing was 500 °C. Alloy powder was held at this temperature for 10 minutes and then compacted under the pressure of 150 MPa for 3 minutes. Additionally, for comparison of the microstructure and chosen properties, one of the compacts was remelted and cast. The microstructures of the compact and cast material were shown in figure 1. During slow cooling of cast Al17Si alloy, a growth of precipitation of primary Si blocks, Si eutectic needle and other phase identified as thick δ Al_4FeSi_2, $Al_5Cu_2Mg_8Si_6$ or Al_2Cu spread over Al matrix was noted [9]. Al17Si alloy compact had homogenous and fine-grained microstructure. Spherical participations were uniformly distributed in Al alloy matrix.

Table.1 Chemical composition of Al17Si alloy.

Si	Fe	Cu	Mg	Zr	Al
17.0	5.0	3.0	1.1	0.6	Balanced

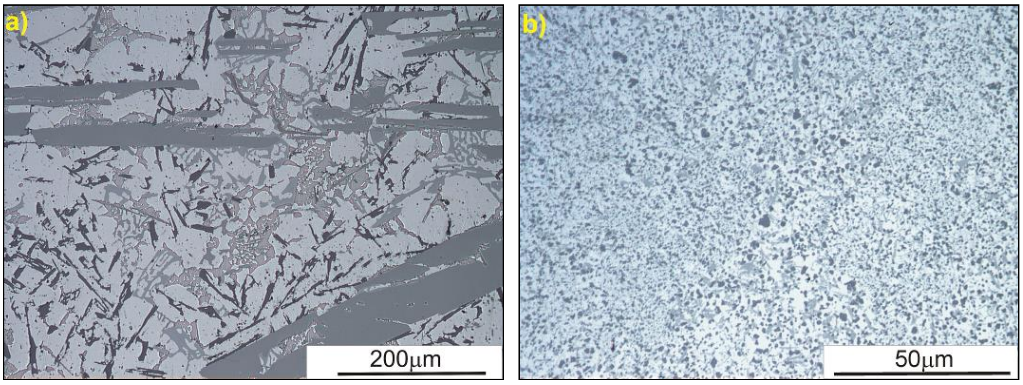

Figure 1. Microstructures of a) cast Al17Si alloy and b) Al17Si alloy compact. Cross-section, unetched.

2.3. Designation of the solid to semi-solid transition temperature

To find the temperature of the first appearance of the liquid state in Al17Si alloy, the thermographic and differential scanning calorimetry (DSC) methods were used. In the thermographic method, the compact with the attached thermocouple was melted in the furnace. The temperature changes in function of time were recorded. Heating curve was presented in figure 2a. During DSC analysis, heat flow changes in a function of the temperature was recorded. To analyse the heat flow curve Origin 8 Pro software was used.

In the result of the investigations, two temperatures of the transition into semi-solid state were obtained. In the first method, the effect related to the beginning of the occurrence of liquid phase was noticed at 505 °C, while in the case of DSC method at about 510 °C. The difference between these two results is thought to be due to the size of the sample used for the tests. Since the DSC method is considered to be more accurate, the temperature of 510 °C was chosen as the solid to semi-solid state transition temperature. The results were consistent with those presented in other research works [9, 10].

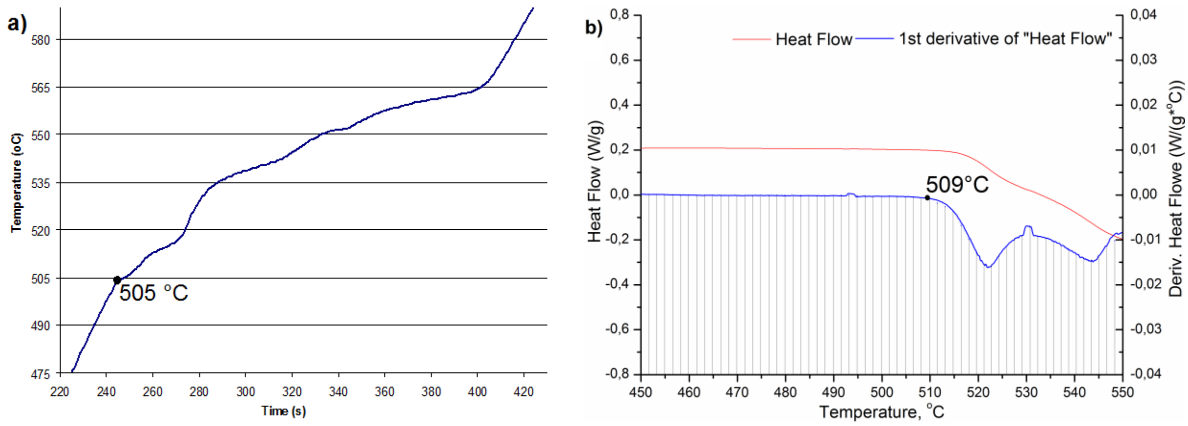

Figure 2. Results of determining the solid to semi-solid transition temperature by a) thermographic method, b) DSC method.

2.4. Extrusion process

The obtained compacts were hot formed in direct extrusion process in isothermal conditions on hydraulic press with hot extrusion system consisting of set of tools and temperature control system. The process was conducted at conventional hot forming temperature as well as in semi-solid state. Extrusion parameters were applied according to table 2. Material obtained after deformation had shape of rod with diameter of 18 mm.

Table 2. The parameters of hot extrusion of Al17Si compacts.

Temperature	Punch velocity	Extrusion coefficient	Die angle	Cooling
490 °C, 510 °C, 520 °C, 530 °C	0.15 mm/s	3.8	45°	Water / room temperature

The changes of extrusion forces in relation to punch displacement during deformation process were recorded. The results were presented in figure 3. Based on the obtained relationships, the value of force corresponding to the stabilization of extrusion process was determined. In the result of increasing temperature from 490 °C - which was assumed as conventional hot forming temperature - to the temperatures where liquid state occurred, the extrusion stabilization forces decreased gradually from 96 kN to 30 kN. These results indicated, that during the material transition from solid to semi-solid state there was a partial change in the deformation mechanism to slip along grain boundaries.

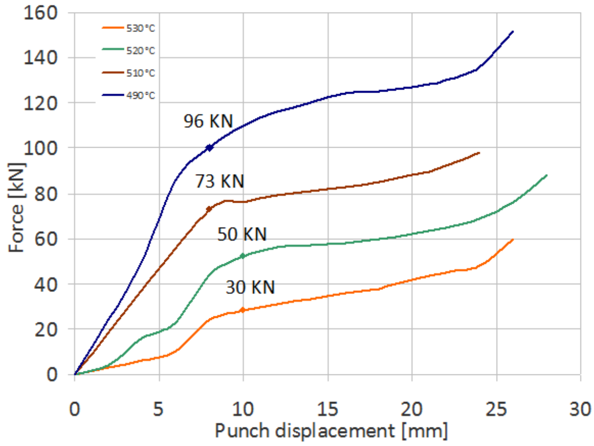

Figure 3. The effect of temperature on the changes in extrusion force in relation to the punch displacement, recorded during hot extrusion of Al17Si alloy compacts.

2.5. Metallographic investigations

The observations of the microstructure of Al17Si alloy compact before and after hot extrusion was conducted using optical microscope LEICA DM4000M. Chosen microstructures were shown in figure 4. The extruded material had very similar microstructure regardless of the extrusion temperature or type of cooling. A fine-grained microstructure was observed in both cases, the dark primary Si particles as well as Si eutectic and other complex phases were uniformly distributed in the α-aluminium matrix. In the case of longitudinal cross-sections material grains did not elongate in the direction of the material flow. Slight grain growth was noticed in the materials deformed at higher temperature or in those cooled at lower cooling rates.

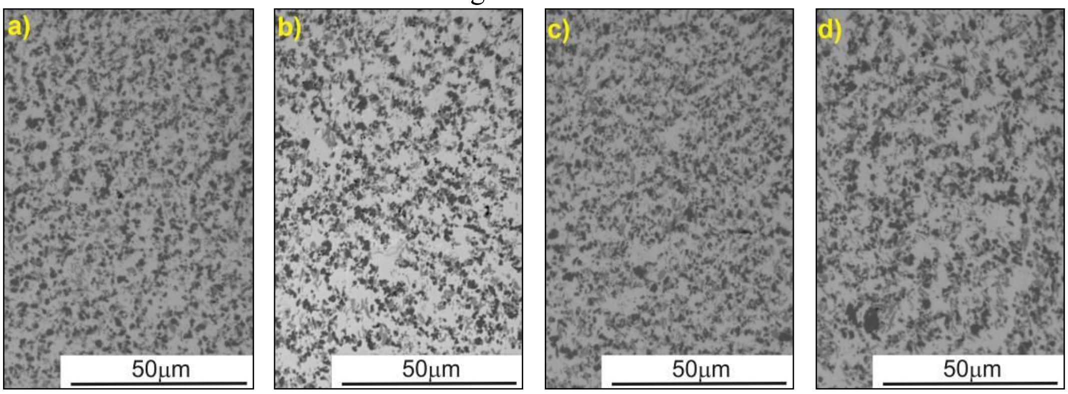

Figure 4. Microstructures of Al17Si alloy after hot extrusion at a) 490°C, b) 520°C cooled in room temperature and c) 510 °C, d) 530 °C cooled in water. Cross-section, unetched.

2.6. Mechanical properties

2.6.1. Hardness measurements

Hardness measurements were conducted by the Vickers method on the compacted and cast Al17Si alloy as well as on the samples after hot extrusion. Hardness was measured on cross-section in the central area of the sample. Table 3 presents average HV_1 values with standard deviation.

Comparing cast Al17Si alloy and Al17Si alloy powder compacts, material obtained from alloy powder had significantly higher (by about 65 HV_1) hardness than cast material. As the result of rapid cooling in water directly after hot extrusion process, hardness of the samples increased by about 10-20 HV_1. In the case of cooling at room temperature, hardness decreased in relation to compact by about

20 HV_1. This effect is related to the growth of Al α-phase grains during slow cooling. Major differences in materials hardness in relation to the changes in extrusion temperature were not observed.

2.6.2. Uniaxial compression tests

The strength of the cast and PM material after hot extrusion was determined in the uniaxial compression tests, which were carried out at room temperature on Instron 1196 machine. Samples with dimensions 12 mm in height and 10 mm in diameter were machined from the investigated materials. Compressive strength of the tested materials are presented in table 3. Figure 5a shows recorded stress- strain curves.

Basing on the results of the tests it was found, that the compressive strength values are comparable for materials produced at conventional hot forming temperature and in the semi-solid state. No significant differences in the nature of stress – strain curves of the extruded materials were observed. A similar material behaviour was noticed in the case of the samples extruded in semi-solid state. Samples deformed at the temperature of conventional hot forming showed better ductility in compression tests. Cast Al17Si alloy had significantly lower mechanical properties than alloy compacts. Figure 5b shows the comparison of chosen mechanical properties.

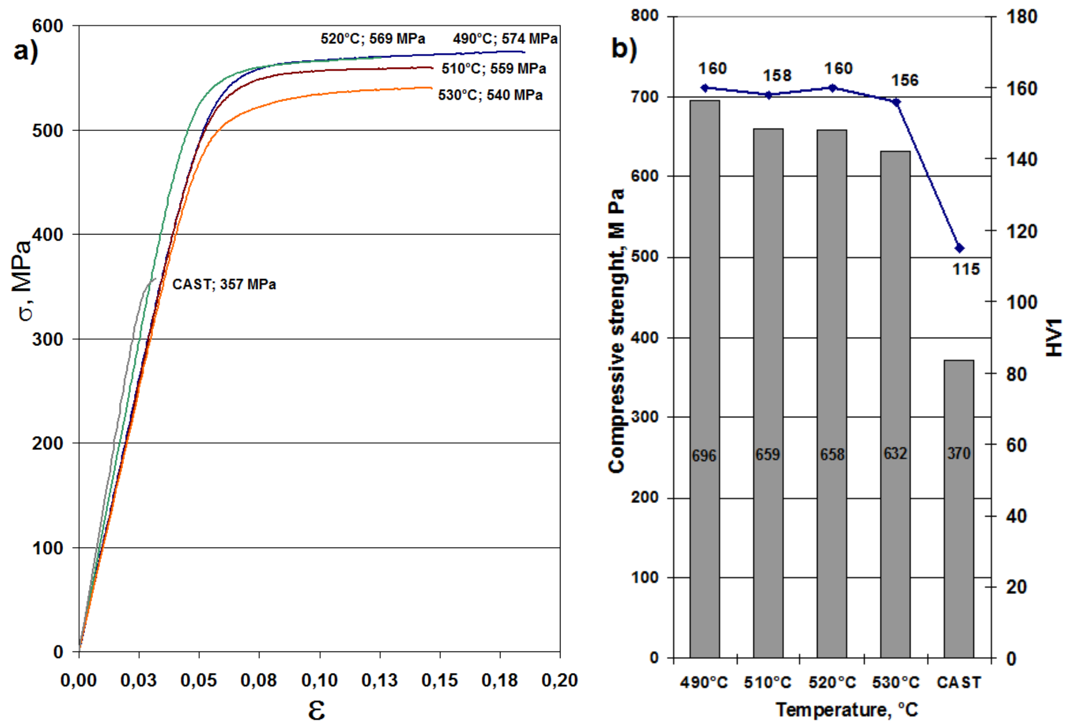

Figure 5. Mechanical properties of the investigated materials: a) stress-strain curves for cast and extruded Al17Si alloy compacts and b) influence of temperature of extrusion of Al17Si alloy on chosen mechanical properties

Table 3. Chosen mechanical properties of cast and PM Al17Si alloy before and after hot extrusion.

	Compact	490 °C		510 °C		520 °C		530 °C		Cast
HV_1	180 ±5	160 ±2	192 ±2	158 ±2	191 ±6	160 ±2	200 ±2	156 ±1	190 ±5	115 ±9
Compressive strength, MPa	-	696 ±22		659 ±14		658 ±27		632 ±15		370 ±6

3. Conclusions

Basing on the results of the investigations the following conclusion can be drawn:

- In the result of DSC and thermographic method it was found, that liquid phase appears in the volume of material at the temperature of 505-510 °C.
- Gradual increase of the extrusion temperature under isothermal conditions led to significant decrease in the level of the forces necessary to carry out deformation process. The nature of force changes indicates the presence of a liquid phase in the material volume at the temperatures above 510 °C.
- Metallographic analysis showed significant differences in the state of the cast material microstructure and materials made by powder metallurgy technology. The use of the fine powder fraction as the starting material resulted in homogeneous microstructure of the material with a significantly smaller grain size. However, significant changes in the microstructure due to increase of the extrusion temperature were not observed.
- The hardness of the samples extruded in the temperature range assumed during the tests was comparable. Differences in hardness resulted from the method of samples cooling and it was approximately 30 HV_1 higher for water-cooled materials, compared to samples cooled at the room temperature.
- The compressive strength of the extruded samples decreased slightly as the process temperature increased. The average compressive strength values for the samples obtained by the powder metallurgy method were significantly higher than for those obtained by casting.
- Isothermal extrusion of powder compacts, carried out under conventional hot forming conditions as well as in the semi-solid state, led to obtaining pore-free products with favourable microstructure and attractive mechanical properties.

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